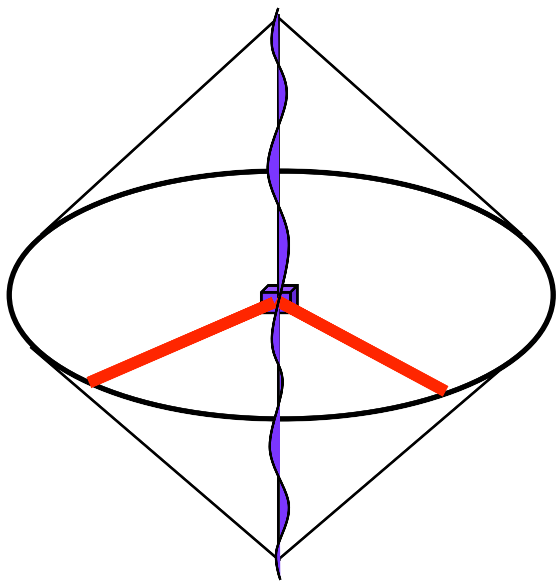
The Fermilab Holometer

a program to measure Planck scale indeterminacy



A. Chou, R. Gustafson, G. Gutierrez, C. Hogan, S. Meyer, E. Ramberg, J.Steffen, C.Stoughton, R. Tomlin, S.Waldman, R.Weiss, W. Wester, S. Whitcomb

Interferometers might probe Planck scale physics

One interpretation of ‘t Hooft-Susskind holographic principle predicts a new kind of uncertainty leading to a new detectable effect:

"holographic noise”

Different from gravitational waves or quantum field fluctuations

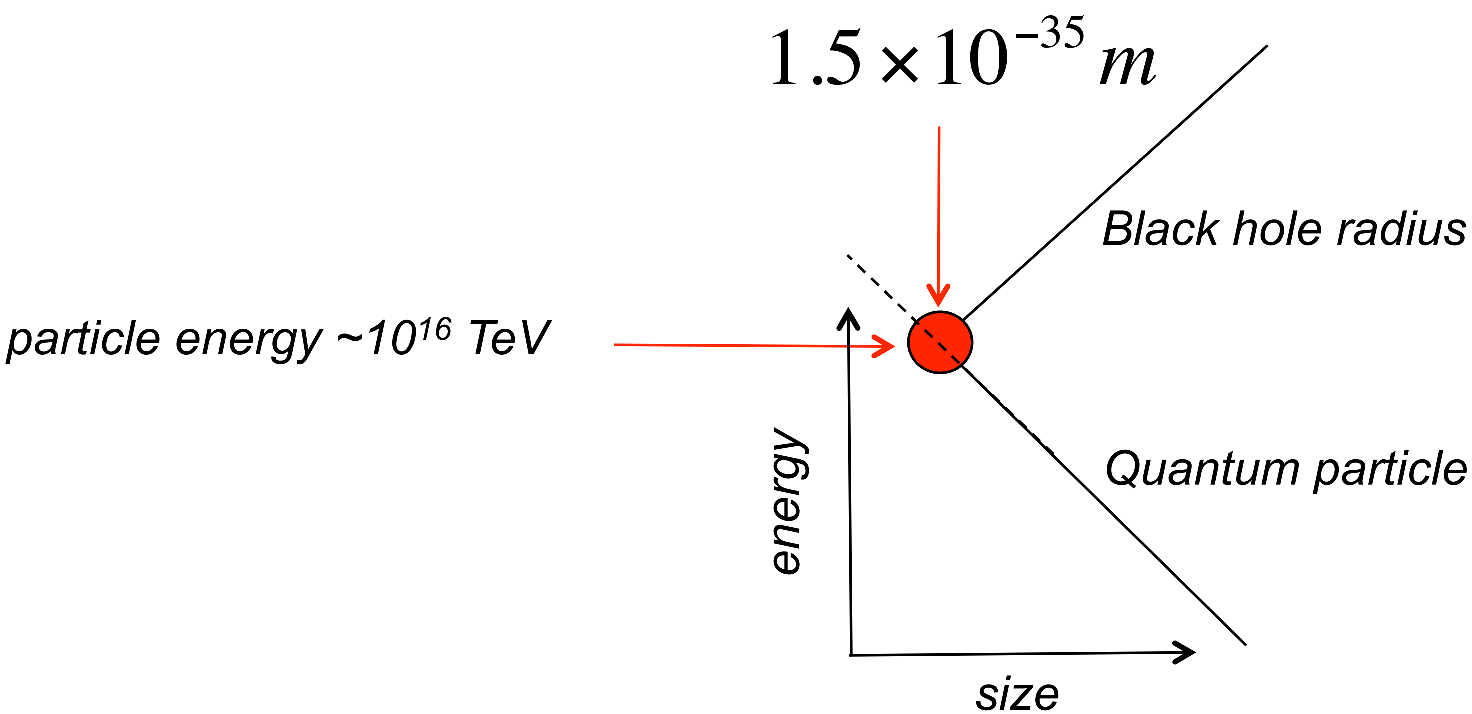
Predicts Planck-amplitude noise spectrum with no parameters

We propose an experiment to test this hypothesis

Planck scale

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \text{ seconds}$$

The physics of this "minimum time" is unknown



Particle confined to Planck volume makes its own black hole

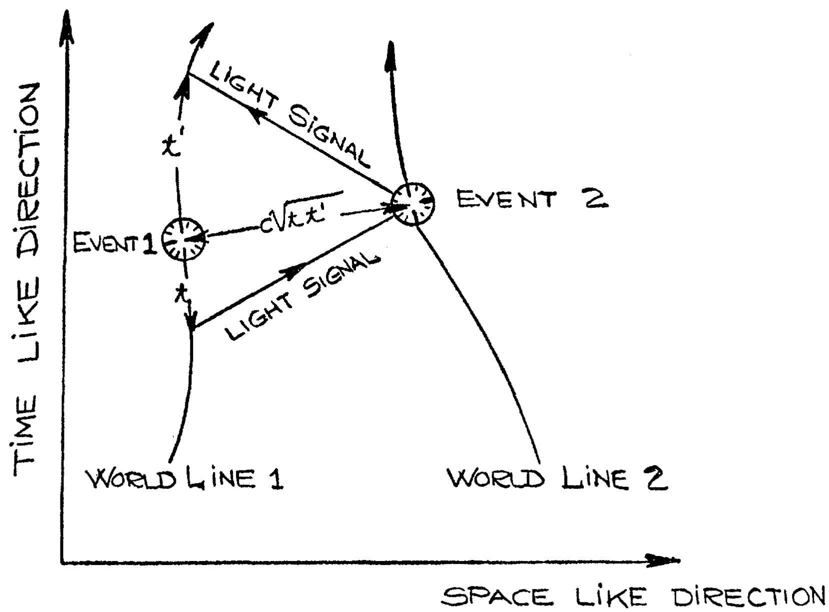
Quantum limits on measuring event positions

Spacelike-separated event intervals can be defined with clocks and light

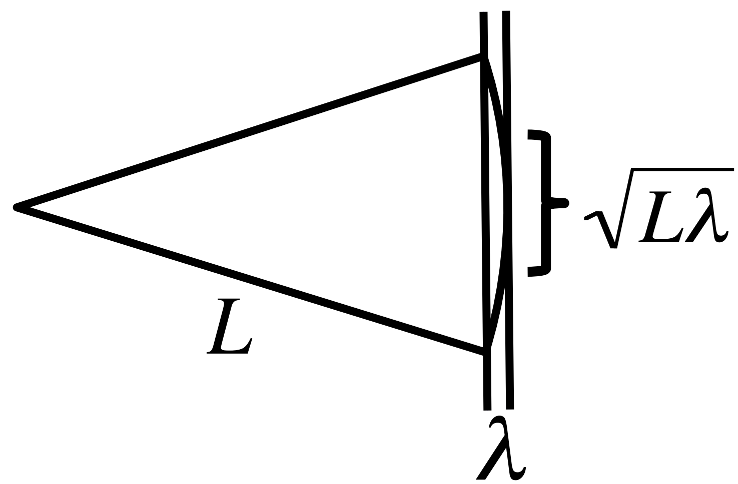
But transverse position measured with waves is uncertain by the diffraction limit

$$\sqrt{L\lambda}$$

This is much larger than the wavelength

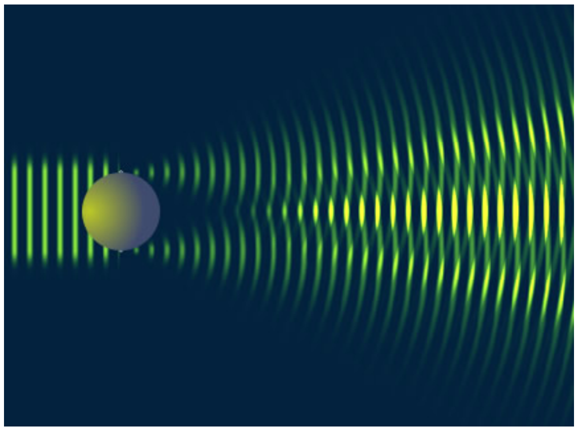


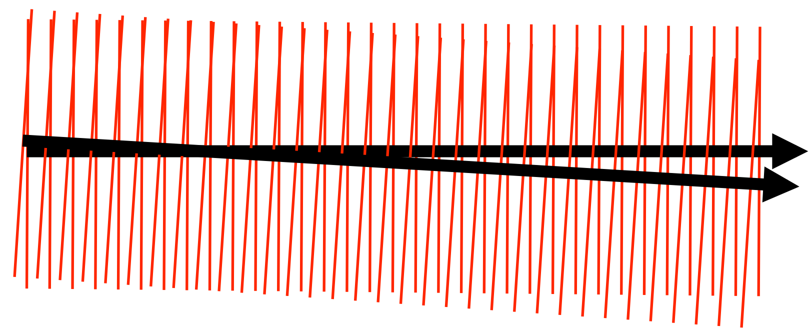
Wigner (1957): quantum limits with one spacelike dimension



Add second dimension: small phase difference of events over large transverse patch

A new uncertainty of spacetime?





Suppose the Planck scale is a minimum wavelength

Then transverse event positions may be fundamentally uncertain by the Planck diffraction limit

Classical path ~ ray approximation of a Planck wave

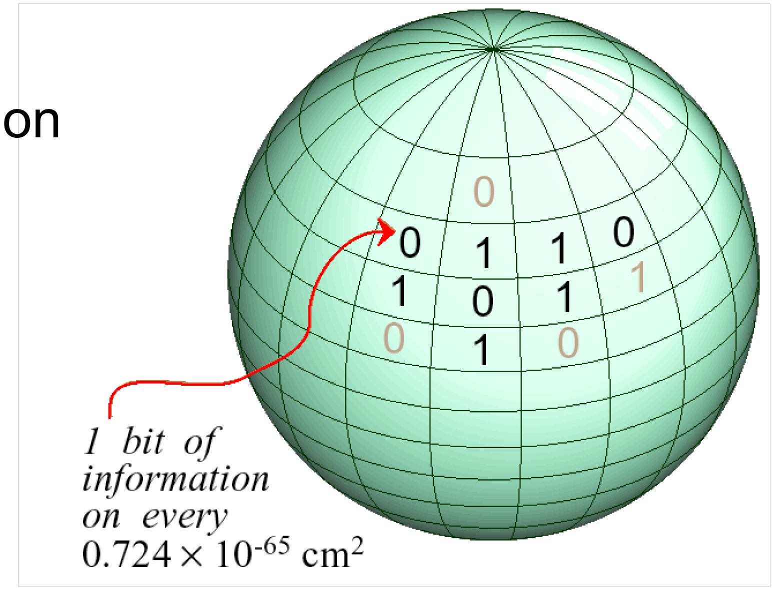
Holographic Principle

Black hole thermodynamics and evaporation

Universal covariant entropy bound

AdS/CFT type dualities in string theory

Matrix theory



All suggest theory on 2+1 D null surfaces with Planck scale bound

But there is no agreement on what it means for experiments

Bekenstein, Hawking, Bardeen et al., 'tHooft, Susskind, Bousso, Srednicki, Jacobson, Banks, Fischler, Shenker, Unruh

Possible consequence of holography

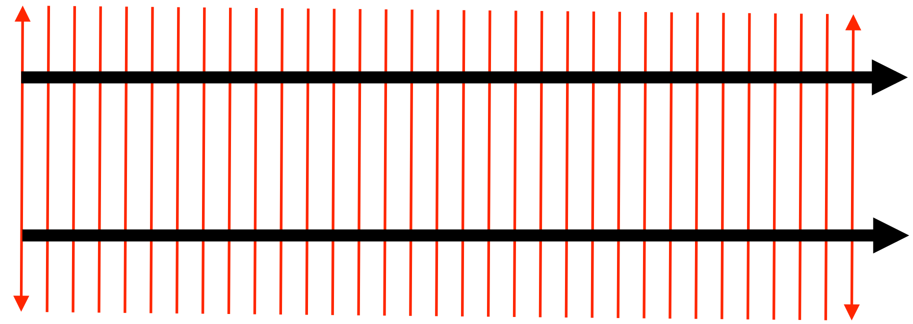
Hypothesis: observable correlations are encoded on light sheets and limited by information capacity of a Planck wavelength carrier (“Planck information flux” limit)

Predicts uncertainty in position at Planck diffraction scale

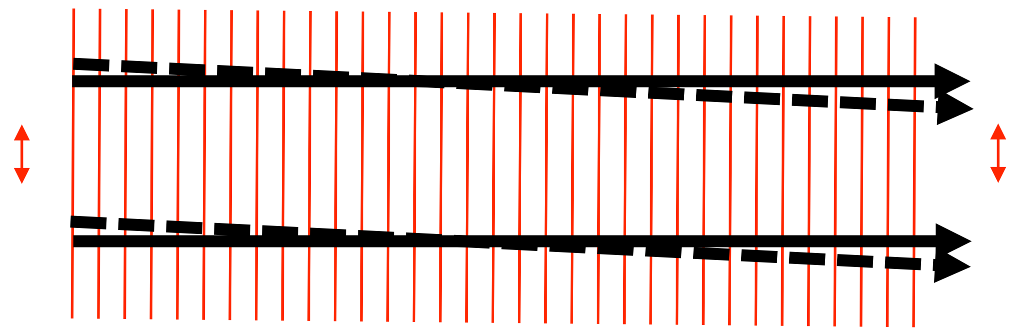
Allows calculation of experimental consequences

- Matter jitters about geodesics defined by massless fields
- ~ Planck length per Planck time
- Only in the transverse (in-wavefront) directions
- Quantum effect: direction depends on measurement
- Coherence of transverse jitter on scale L

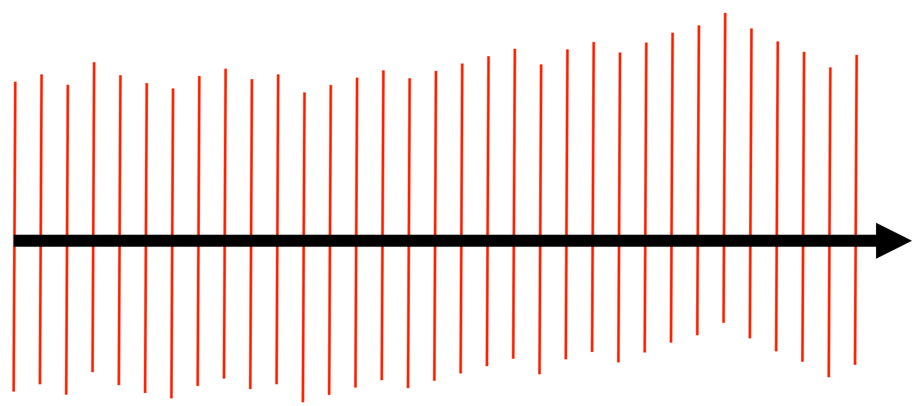
Rays in direction normal to Planck wavefronts



Localize in wavefront: transverse momentum, angular uncertainty



Interpret as wavefunction of position: transverse uncertainty, Planck diffraction/jitter



Survey of theoretical background: arXiv:0905.4803

Arguments for the new indeterminacy

- Information bounds, black hole evaporation, matrix theory

Arguments for spatial coherence of jitter

- Locality, isotropy, matrix theory

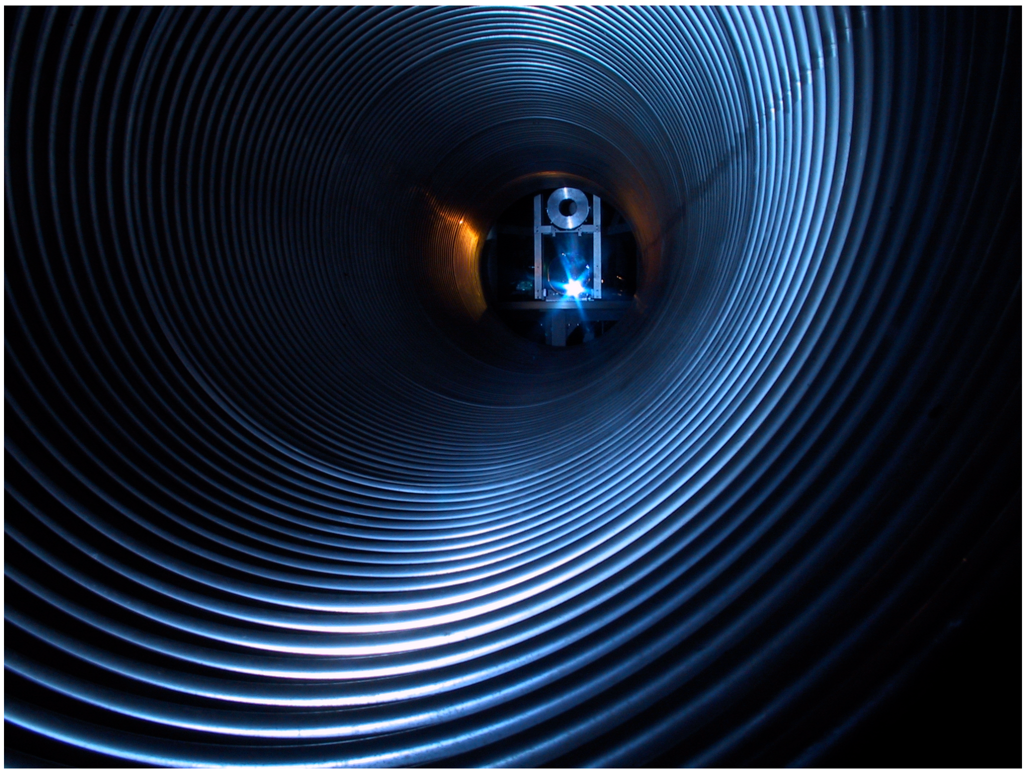
Ways to calculate the noise

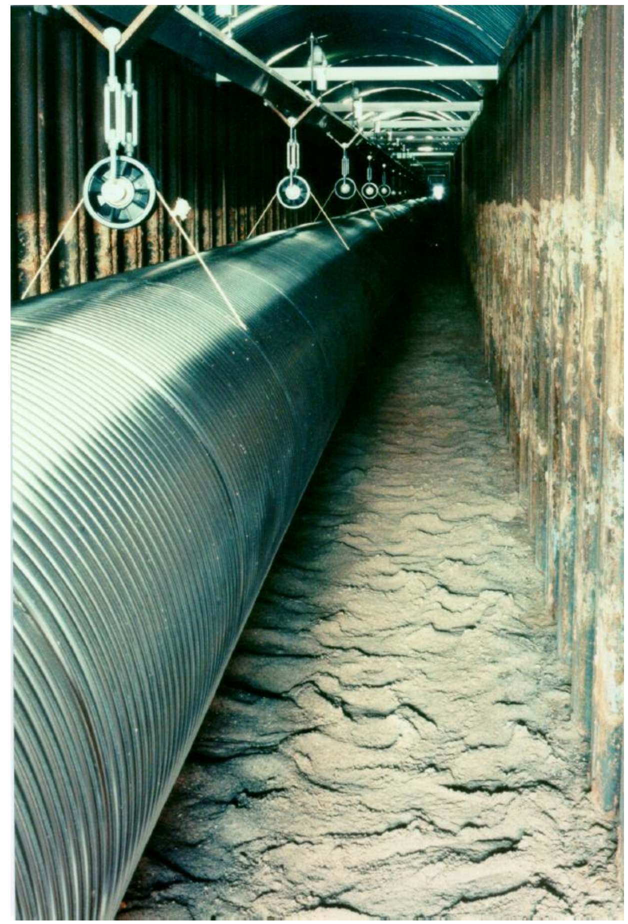
- Wave optics
- Planck wavelength interferometer limit
- Precise calibration from black hole entropy

No argument is conclusive: motivates an experiment!

Attometer Interferometry

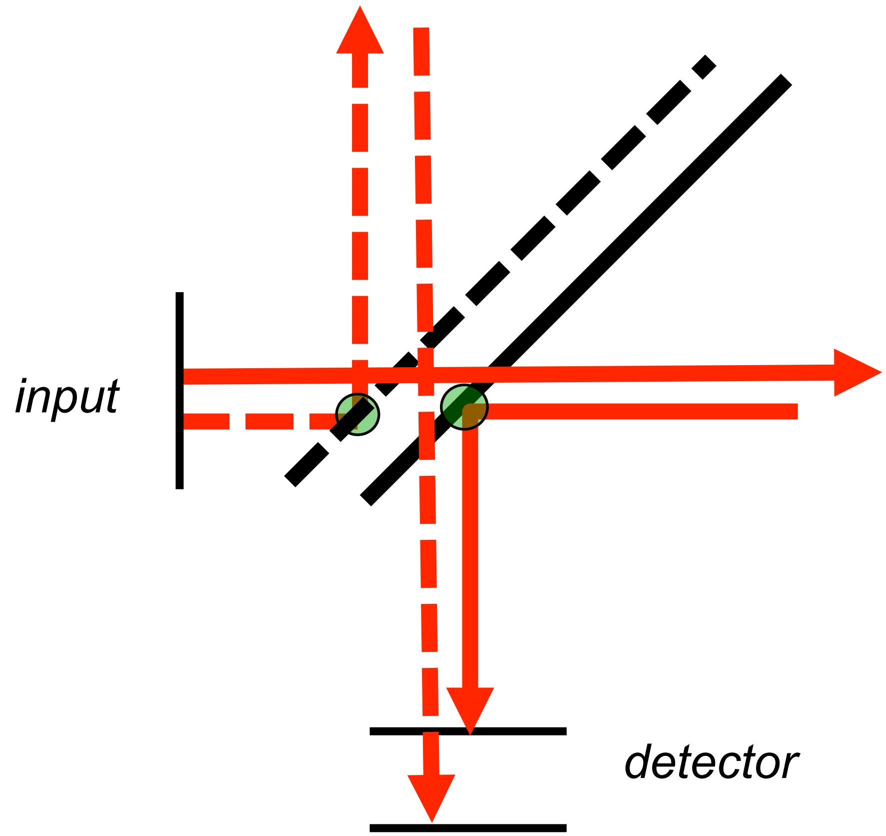
Interferometers now measure transverse positions of massive bodies to $\sim 10^{-18}\, m/\sqrt{Hz}$ *over separations* $\sim 10^3\, m$





Holographic noise in a Michelson interferometer

Jitter in beamsplitter position leads to fluctuations in measured phase



Range of jitter depends on arm length:

$$\Delta x^2 = l_P L$$

this is a new effect predicted with no parameters

Universal Holographic Noise

Spectral density of strain noise independent of frequency:

$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22} \mathrm{Hz}^{-1/2}$$

Detected noise spectrum can be calculated for a given apparatus

CJH: arXiv:0712.3419   Phys Rev D.77.104031 (2008)
CJH: arXiv:0806.0665   Phys Rev D.78.087501 (2008)
CJH & M. Jackson: arXiv:0812.1285 Phys Rev D.79.12400 (2009)
CJH: arXiv:0905.4803

Strategy for Our Experiment

Direct test for the holographic noise

- Positive signal if it exists

Sufficient sensitivity

- Provide margin for prediction
- Probe systematics of perturbing noise

Measure properties of the holographic noise

- Frequency spectrum
- Spatial correlation function

Correlated holographic noise in nearby interferometers

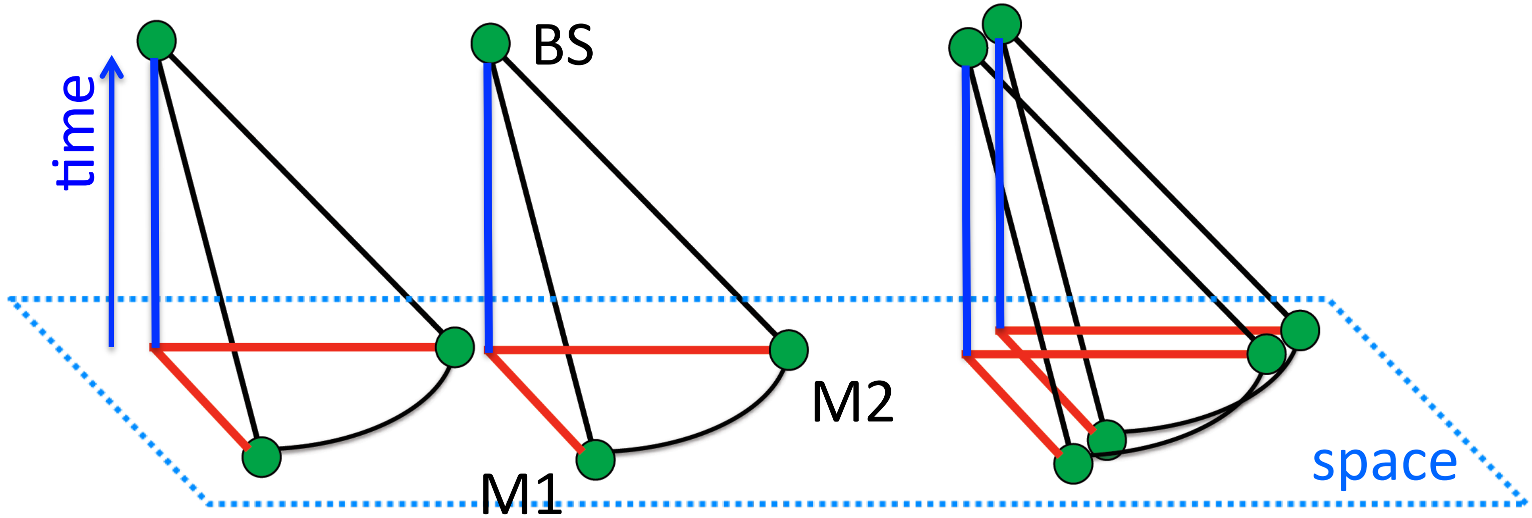
Matter on a given null wavefront "moves" together

- no locally observable jitter should depend on remote measurements
- phase uncertainty accumulates over *~L*

Spacelike separated measurements within causal diamond must collapse into the same quantum state

Nonoverlapping spacetime volumes, uncorrelated noise

overlapping spacetime volumes, correlated holographic noise



Experiment Concept

Measurement of the correlated optical phase fluctuations in a pair of isolated but collocated power recycled Michelson interferometers

- exploit the spatial correlation of the holographic noise
- use the broad band nature of the noise to measure at high frequencies where other correlated noise is expected to be small

Broadband system noise is uncorrelated

Coherently build up holographic signal by cross correlation

holographic signal = photon shot noise after

$$t_{\rm obs} > \left(\frac{h}{P_{\rm BS}}\right)^2 \left(\frac{\lambda_{\rm opt}}{\lambda_{\rm Pl}}\right)^2 \left(\frac{c^3}{32\pi^4 L^3}\right)$$

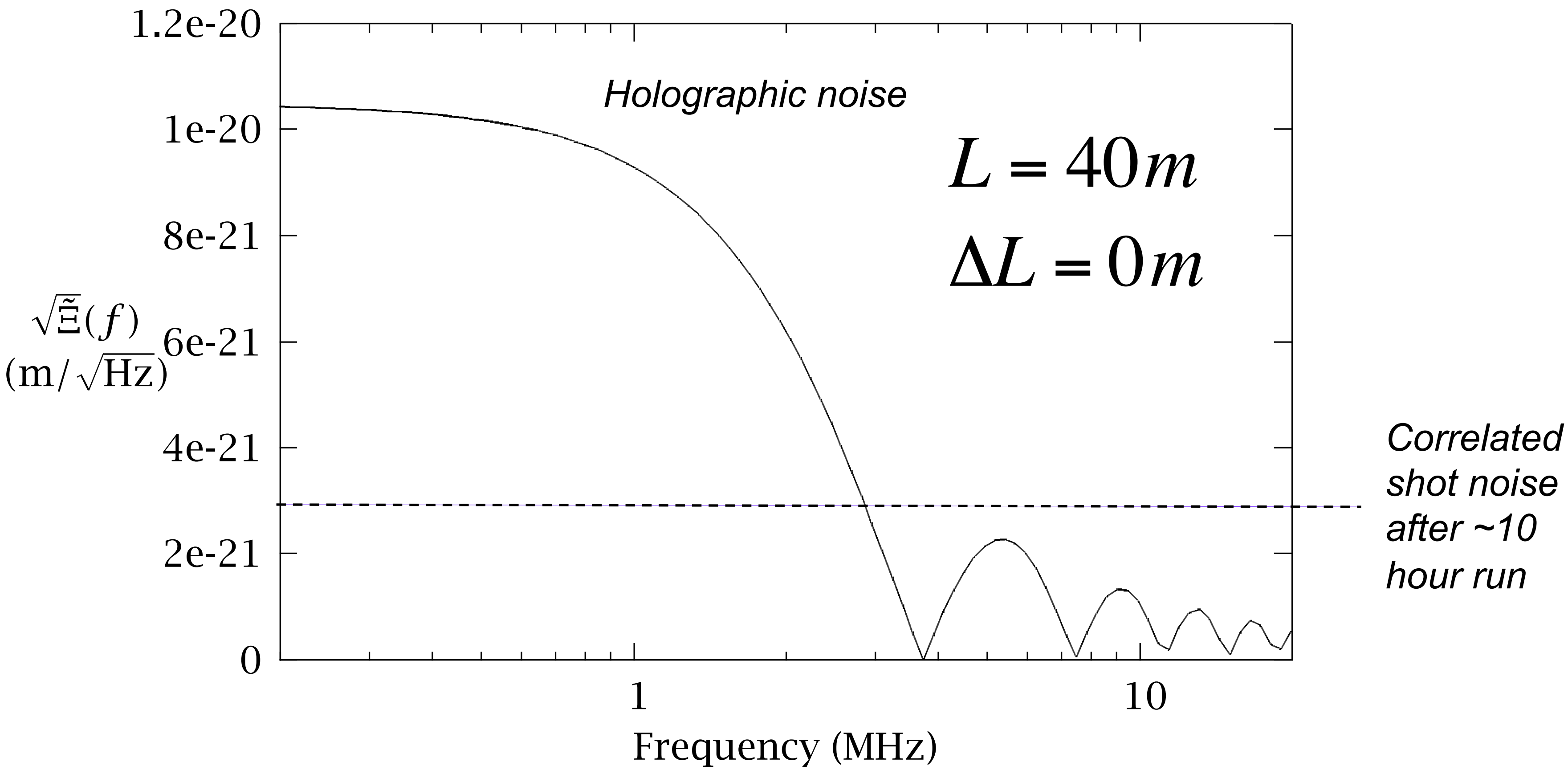
For beamsplitter power P_{BS}=2 kW, arm length L=40m, time for three sigma measurement is ~ 30 minutes

Thermal lensing limit on beamsplitter power drives design

Reject spurious correlations in the frequency domain

Predicted Planck-amplitude frequency spectrum

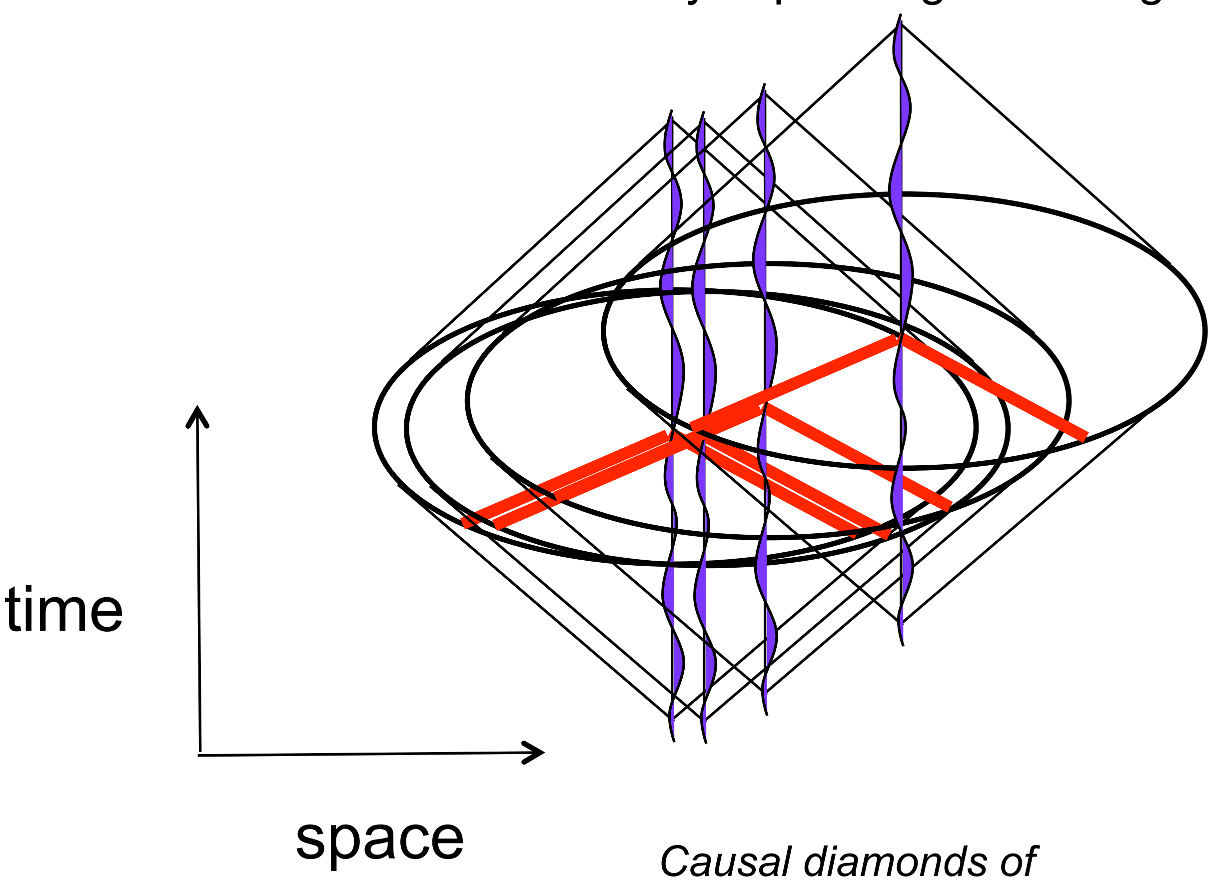
$$\tilde{\Xi}(f) = \frac{c^2 2t_P}{\pi(2\pi f)^2}[1 - \cos(f/f_c)], \qquad f_c \equiv c/4\pi L$$



Reconfigure apparatus to modulate the signal

Measure correlated optical phase fluctuations in the two Michelson interferometers at different separations and orientations

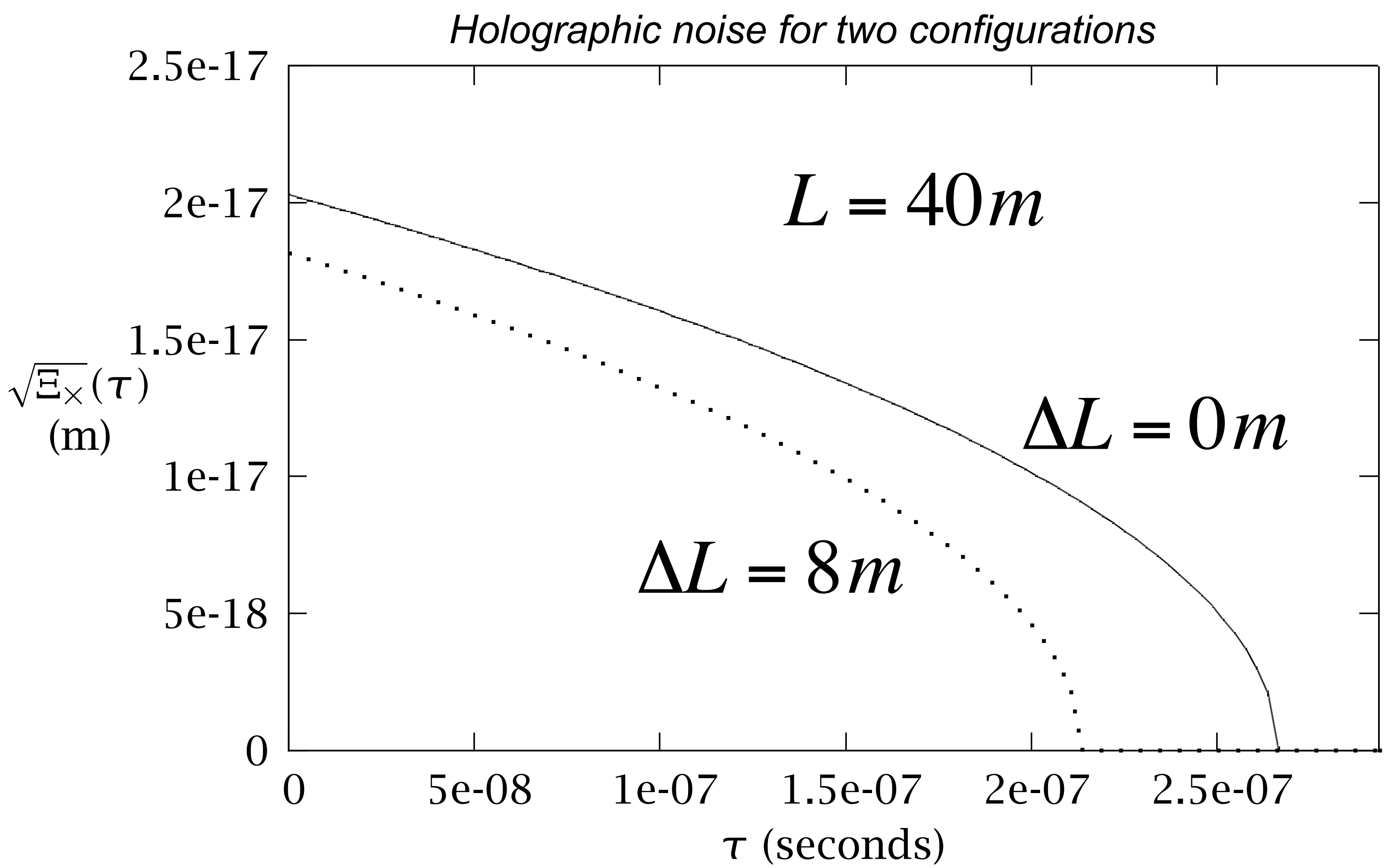
Modulate the correlation by separating or misaligning the interferometers



Causal diamonds of beamsplitter signals

Predicted time-domain correlation, decorrelation

$$\begin{aligned} \Xi_\times(\tau) &\approx (\lambda_P/\pi)(2L - 2\Delta L - c\tau), \qquad 0 < c\tau < 2L - 2\Delta L \\ &= 0, \qquad c\tau > 2L - 2\Delta L. \end{aligned}$$



Interferometer design informed by LIGO experience

Simple optical design

Extensive experience with similar systems
Much easier than gravitational wave detection

Well tested components

Mirror specifications in routine range
Most components off the shelf
Staged commissioning limits technical risk

Comparison of phase noise

Interferometer	**Power on beam splitter, watts**	**Phase noise, rad/sqrt(Hz)**
LIGO Phase noise interferometer (1998)	70	3×10^{-10}
LIGO H1,L1 (2009)	250	2×10^{-11}
GEO 600 (2009)	2700	8×10^{-12} /SRGain
Proposed instrument	2000	9×10^{-12} @ f > 10kHz

LIGO Phase Noise Test Interferometer

VOLUME 80, NUMBER 15 PHYSICAL REVIEW LETTERS 13 APRIL 1998

High Power Interferometric Phase Measurement Limited by Quantum Noise and Application to Detection of Gravitational Waves

P. Fritschel, G. González,* B. Lantz, P. Saha,† and M. Zucker
Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 17 November 1997)

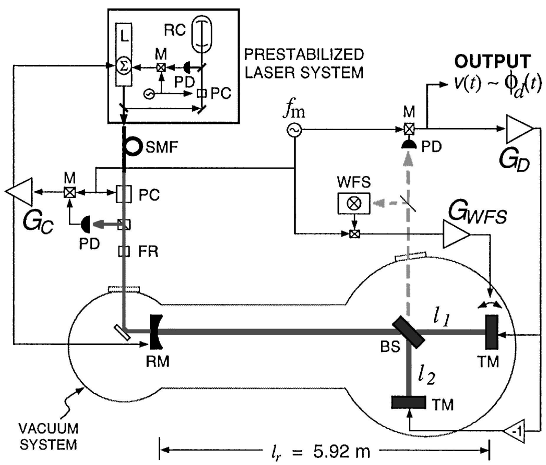


FIG. 1. Simplified schematic of the interferometer. Symbols are as follows: PC: Pockels cell; FR: Faraday isolator; TM: test mass (high reflector); BS: beam splitter, RM: recycling mirror; SMF: single mode fiber; RC: reference cavity; M: mixer; WFS: wave front sensor; L: laser; G_D: differential length controller; G_C: common length and frequency trim controller; and G_{WFS}: alignment controller.

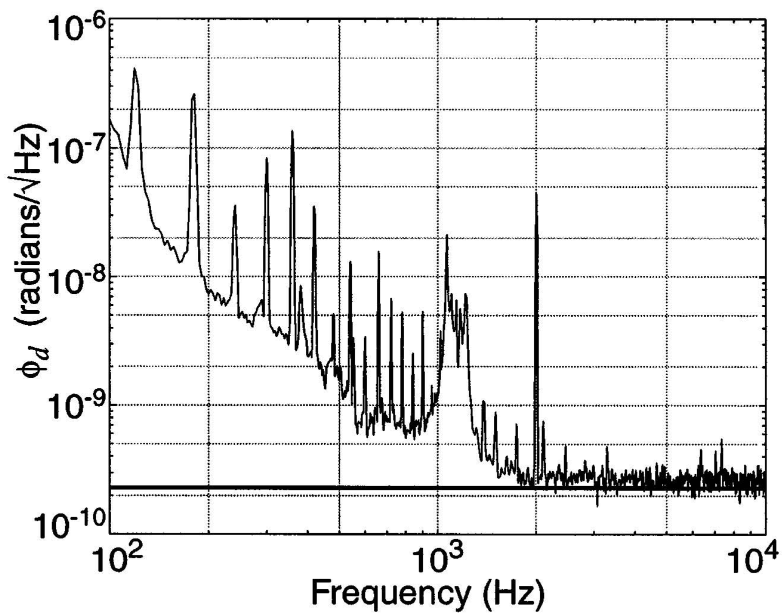


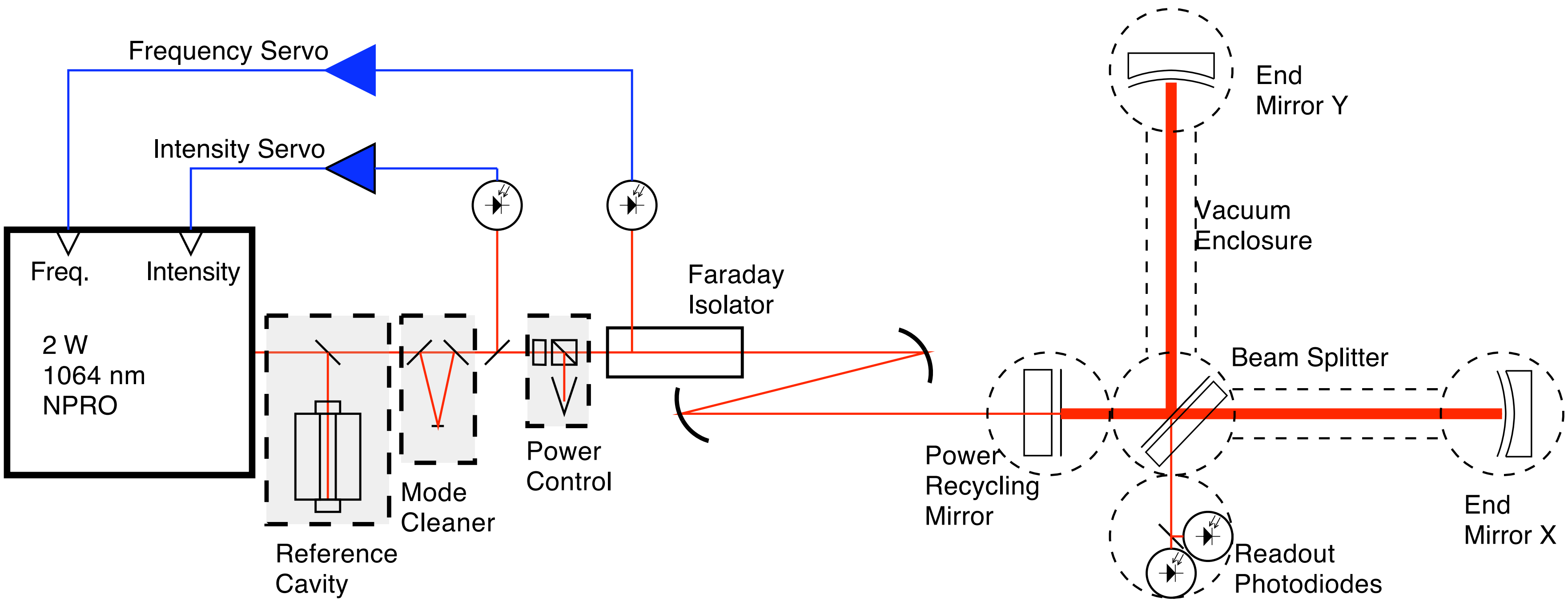
FIG. 2. Amplitude spectral density of the equivalent Michelson phase difference ϕ_d. The predicted shot noise limited level for the measured system parameters is indicated by the straight solid line. The peak at 2 kHz is a calibration line. The plot is a composite of two fast Fourier transforms; the resolution bandwidth in the 1.2–10 kHz band is 18.7 Hz, and in the 100 Hz–1.2 kHz band is 4.7 Hz.

High frequency noise: dominated by photon shot noise

Optical layout: standard power-recycled Michelson

Simple initial design: 4 optics each

Add other components as needed



S. Waldman, MIT

Vacuum system

~ 10^{-6} Torr

Fast pump down

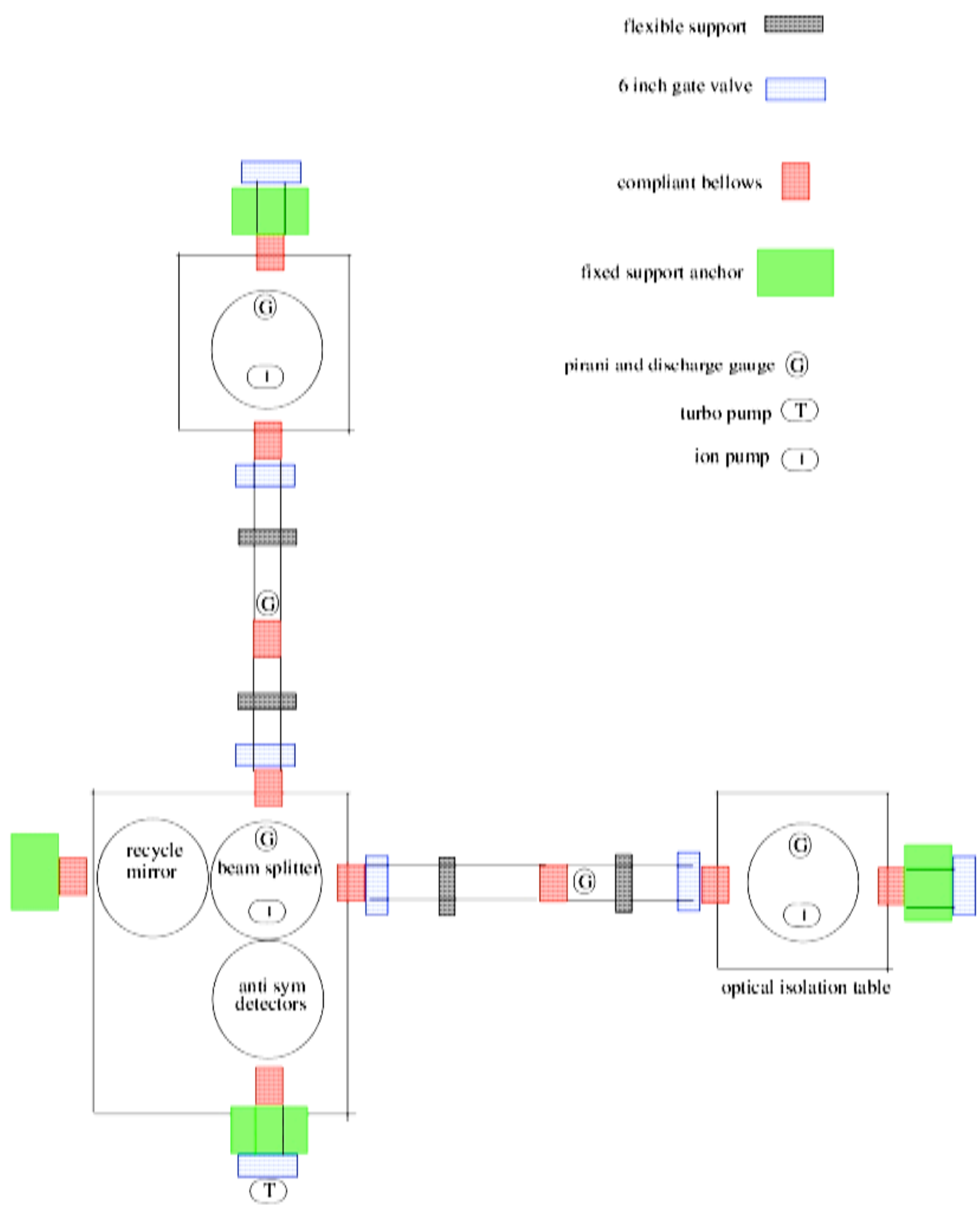
access, mobility

Clean 304 steel

6 in diameter, 10 foot tubes

24 in vacuum vessels

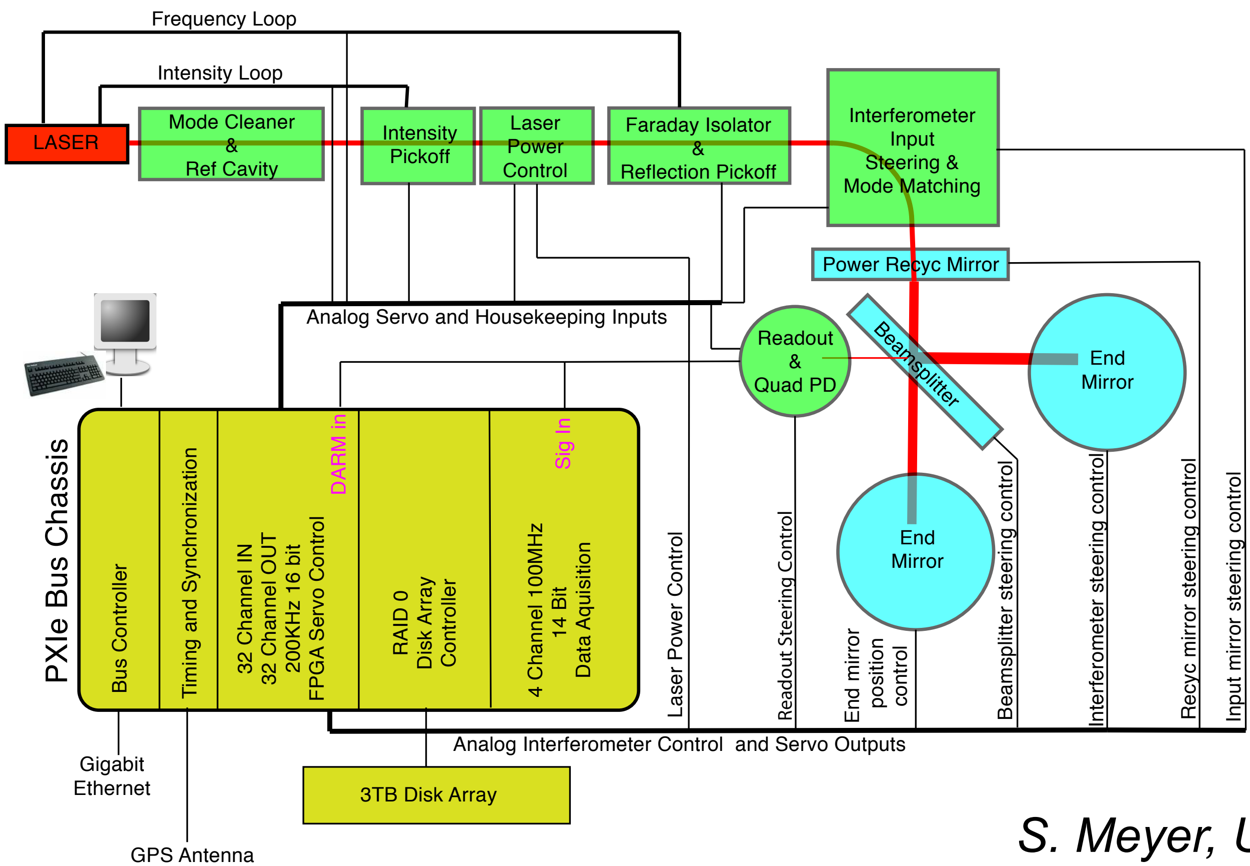
standard and semi-custom components



Control & data system

Off-the-shelf components and control software

Design allows detailed RF noise diagnostics



S. Meyer, U. Chicago

Budget & Schedule

- Design phase: $226K M&S + $96K non-scientist effort
- Construction phase: $977K M&S + $58K non-scientist effort
  - Total construction with 50% contingency: $1.55M
- Operations for 3 years: $970K M&S + $381K non-scientist
  - Includes significant commissioning time
  - Closed-ended program to achieve goals
  - Null result (1 configuration) could be achieved sooner
- Final budget, schedule, technical review before proposal
  - Add professional engineering, design
- Scientist team: ~4 FTE for ~ 4 years

Status of the Fermilab Holometer

- Team:
  - Fermilab (A. Chou, G. Gutierrez, CJH, E. Ramberg, J. Steffen, C. Stoughton, R. Tomlin, W. Wester, + others TBD)
  - MIT (R.Weiss, S.Waldman)
  - Caltech (S. Whitcomb)
  - University of Chicago (S. Meyer + students to be added; funded by FRA)
  - University of Michigan (R. Gustafson)
  - includes LIGO experts
- Building tabletop prototypes at Fermilab
  - Successful edge-locked interferometer, power recycled cavity
- Designed 40m system
- FCPA mini-review report available
  - Panel included external LIGO & GEO600 experts, theorist
- After PAC & Director approval: engineering design, detailed technical review, DOE Field Work Proposal

June 2009 PAC letter

"*Questions that should be widely addressed include:"*

1. "*How generic is this prediction?"*
   – Derived from very general principles, but as yet no fundamental theory
2. "*Is the idea already excluded by other constraints?"*
   – No.
3. *"What would we learn from a negative result?"*
   – Physical position state correlations exceed Planck information bound.
4. *"Can the effect be excluded by GEO600 in the near future?"*
   – System noise, and uncertainties in absolute calibration, would have to be reduced by a factor of a few above about 500Hz. This may be difficult, but some members of the GEO600 team believe that they can do it in 2010.
5. *"What sensitivity goals should be pursued in a more general framework?"*
   – After significant exclusion of Planck level predicted noise, the program should terminate; laser work should migrate to axion cavities.
   – If the effect is detected, pursue higher precision tests

Science Outcomes

If noise is not there,

Constrain interpretations of holography

But no direct challenge to widely cherished beliefs

If it is detected, experiments probe Planck scale unification

Study holographic relationship between matter, energy, space, time

Shape interpretation of fundamental theory

Backup slides

(həʊˈlɒmɪtə(r)) [f. HOLO- + -METER, Cf. F. *holomètre* (1690 Furetière), ad. mod.L. *holometrum*, f. Gr. ὁλο- HOLO- + μέτρον measure.]

1696 PHILLIPS (ed. 5), *Holometer*, a Mathematical Instrument for the easie measuring of any thing whatever, invented by Abel Tull. **1727-41** CHAMBERS

Uncertainties and decisions to be made

- In vacuum or outside detectors
  - begin with outside detectors, decide from initial noise performance
- PZT hard optics mounts or suspensions
  - begin with PZT, decide from required locking dynamic range
- Alignment servos
  - begin with simple adjustment, add dither servo alignment if needed
- Laser frequency stabilization and filtering
  - begin with only interferometer common mode feedback to laser, add in-line filter cavity and active frequency stabilization to reference cavity if needed

Data

- High SNR in ~ 1 hour
- 6 Tb total per 10 hour run
- Whole dataset does not need archiving
- Relevant correlation and housekeeping data compresses to ~40Gb per 10 hour run
- ~tens of Tb for whole project

Other elements

- commercial optical tables, vibration isolation
- commercial portable clean rooms
- commercial 40m by 80m space
  warehouse lease: fast, flexible
  Seismic and RF pre-occupancy survey

Schedule

Task	Design ongoing until March, 2010	Construction March 2010 - June 2010
DAC System	purchase one system; 4 weeks lead time	purchase second system; 4 weeks lead time
Laser Table Optics	small table training and development; 12 weeks	purchase; 4 week lead time
Interferometer Optics	”	purchase; 10 week lead time
Intensity and Frequency Servos	”	
Operations Site Computing	requirements analysis and implementation plan; 2 weeks	purchase; 1 month lead time
Fermilab Computing	analyze disk/tape/robot options; 2 weeks	
Vacuum Vessels and Tubes	vet design; 8 weeks	purchase; 10 weeks lead time
Vacuum Pumps and Instrumentation	”	”
Support Stands	design; 2 weeks	fabricate; 8 week lead time
Baffles	design and prototype; 7 weeks	fabricate; 4 week lead time
Laser Table (mechanical)	design; 2 weeks	fabricate baffle; 4 week lead time
Portable Clean Room		purchase; 6 week lead time
Safety	review laser and vacuum design and operations plans; 1 week	
Warehouse	8 weeks specify	8 weeks bid and approve

M&S costs

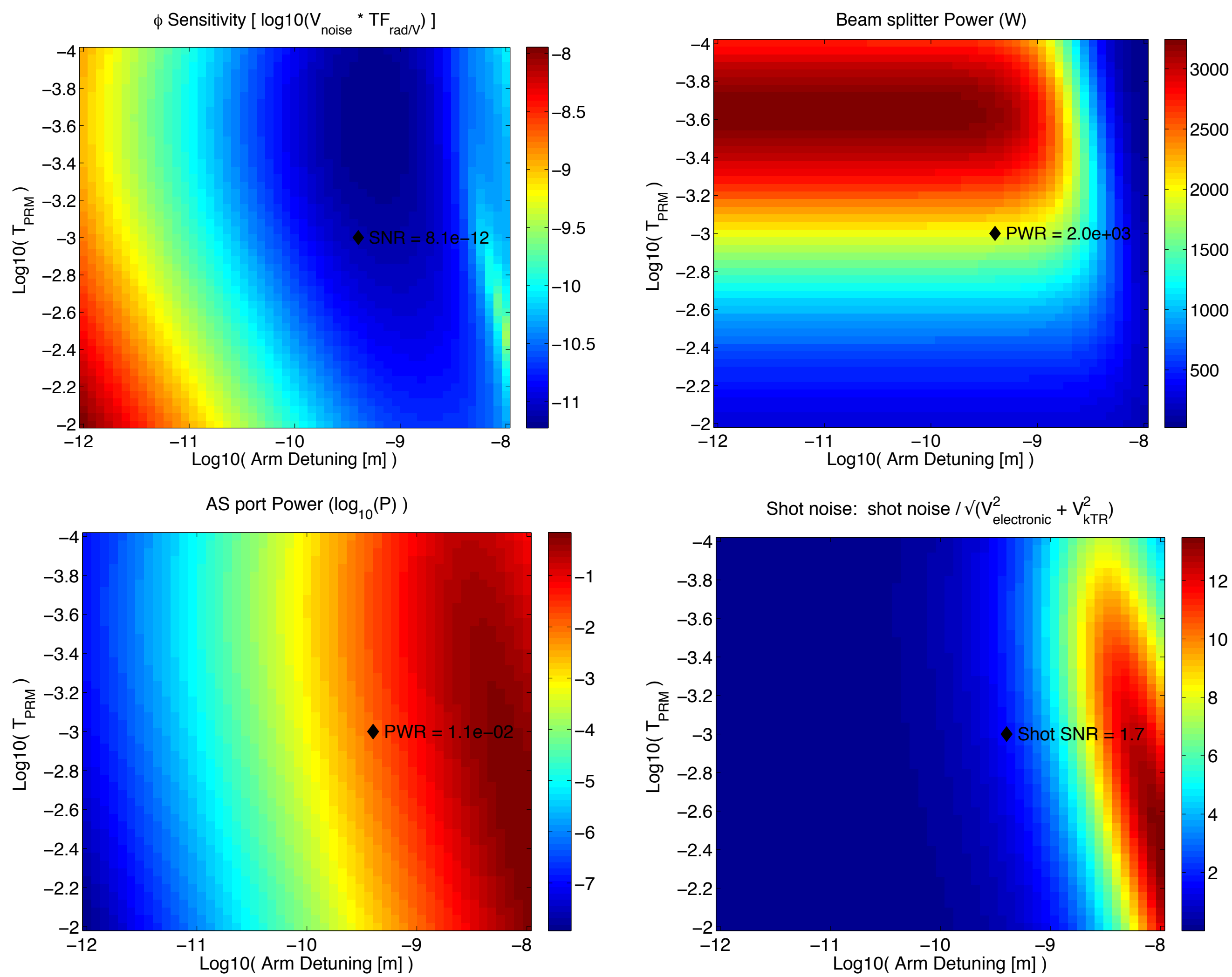
Task	Design	Construction	Operations
DAC System	$54K	$54K	
Laser Table Optics	$140K	$140K	
Interferometer Optics		$68K	
Intensity and Frequency Servos	$32K	$32K	
Operations Site Computing		$40K	
Fermilab Computing			$70K for 70 TByte
Vacuum Vessels and Tubes		$250K	
Vacuum Pumps and Instrumentation		$175K	
Baffles		$10K	
Portable Clean Room		$48K (Terra Universal web)	
Support Stands		$30K	
Laser Table (mechanical)		$120K	
Safety		$10K (goggles, partitions, interlocks)	
Warehouse			$900K
TOTAL	$226K	$977K	$970K

Non-scientist effort

Task	Design	Construction	Commissioning (6 months)	Measurement
DAC System				
Laser Table Optics	1.00 EP	1.00 EP	1.00 EP	
Interferometer Optics				
Optics Mounts				
Intensity and Frequency Servos	2.00 EE; 0.50 MT	4.00 ET	0.50 ET	
On Site Computing	0.25 CP		0.25 CP	
Off Site Computing	0.25 CP			
Vacuum Vessels and Tubes	0.25 ME		1.00 MT	continuing 0.25 FTE MT
Vacuum Pumps and Instrumentation	0.25 ME		1.00 MT	continuing 0.25 FTE MT
Support Stands	0.25 ME		1.00 MT	
Baffles	1.00 ME		1.00 MT	
Laser Table (mechanical)	0.25 ME		1.00 MT	
Portable Clean Room			1.00 MT	
Safety				
Warehouse				continuing 0.5 FTE MT
TOTAL non scientist FTE months	6.0	5.00	7.75	continuing 1.0
Cost w/OPTO/vac/fringe/overhead	$98k	$58k	$84k	$297k

Table 9: FTE months non scientist effort: CP=computing professional; MT=mechanical tech; EE=Electronics Engineer; ET=Electronics tech; ME=mechanical engineer; EP=engineering physicist. The FTE cost uses PPD rates for FY2009 inflated by 3%, with OPTO, vacation, fringe, and overhead included.

Optimized cavity parameters



S. Waldman

About the optics

- All optics requirements can be met by (now) standard superpolish surfaces coated by plasma thin film deposition.
- To avoid thermal lensing in the beam splitter will need to use low loss Heraeus fused silica such as Supersil 3001/3002/300.
- Purchase dedicated coating runs with commercial vendor for initial components and spares.
- Use vacuum compatible PZT controlled 2” optics mounts being developed in industry by the Advanced LIGO project.

Experiment parameters

Input laser power @ 1.06 m	0.75 watt
Arm length BS - EM	40 meters
Free spectral range recycling cavity	3.5 MHz
Min. beam waist diameter	7.4 mm
Power recycling arm length	0.5 meter
End mirror transmission	10ppm
Beam splitter transmission	0.5
Anti reflection coating reflectivity	10 ppm
Mirror loss (PRM,BS,TM)	50 ppm
Substrate loss	10 ppm
Differential arm loss	25 ppm
Power on BS	2 kW
Differential length offset	4×10^{-10} meters = 4×10^{-4} l
Output power at antisym	10 mW 5mW / detector
Recycling mirror transmission	1.0×10^{-3}
Recycling cavity frequency pole	365 Hz
Transimpedance of preamp	100 ohms
Preamp voltage noise	3nV/sqrt(Hz)
Quantum phase noise	8×10^{-12} radians/sqrt(Hz)

Goals of the Fermilab Holometer

1. Measure spatiotemporal cross correlation of two interferometers to sub-Planck precision
2. Design apparatus to provide convincing evidence for universal holographic noise, or an upper limit well below Planck amplitude
   - Turn noise into a signal that increases linearly with time
   - Measure predicted signatures to high precision: frequency spectrum, time domain correlation
   - Modulate signal by reconfiguring apparatus
   - Signal measured at MHz frequencies, ~1000 times GEO600
3. Help ongoing cavity technology development at Fermilab for future axion regeneration experiment